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Dinosaur Tracks from the Cedar Mountain Formation (Lower Cretaceous), Arches National Park, Utah

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The seventh and largest known dinosaur tracksite from the Cedar Mountain Formation is reported from two important stratigraphic levels in the Ruby Ranch Member within the boundaries of Arches National Park. Previous reports of sites with a few isolated tracks are of limited utility in indicating the fauna represented by track makers. The Arches site reveals evidence of several theropod morphotypes, including a possible match for the coelurosaur *Nedcolbertia* and an apparently didactyl *Utahraptor*-like dromeosaurid. Sauropod tracks indicate a wide-gauge morphotype (cf. *Brontopodus*). Ornithischian tracks suggest the presence of an iguandontid-like ornithopod and a large ankylosaur. Dinosaur track diversity is high in comparison with other early Cretaceous vertebrate ichnofaunas, and it correlates well with faunal lists derived from skeletal remains, thus providing a convincing census of the known fauna.

Keywords Cedar Mountain Formation, Arches National Park, didactyl tracks, dromeosaur tracks, Early Cretaceous

INTRODUCTION

Only recently have dinosaur tracks been reported from the Early Cretaceous Cedar Mountain Formation (Lockley et al., 1999). Although dinosaur tracks and other vertebrate tracks are relatively common in the underlying Upper Jurassic, Morrison Formation (Lockley et al., 1998) and the overlying mid-Cretaceous (Late Albian to Early Cenomanian) Dakota Group (Lockley et al., 1992; Lockley and Hunt, 1995), they are still poorly known in the intervening Cedar Mountain Formation. Most known sites reveal only a handful of tracks that fall into broad taxonomic categories such as theropod, sauropod, and ornithopod (Lockley et al., 1999). None of the previously reported sites warranted detailed description since the tracks were not of exceptional quality nor sufficiently numerous to allow more than the most general paleobiological inferences.

The present study, however, deals with a new, and significantly larger site, found in 2000, during a paleontological survey of Arches National Park. (Fig. 1) The site is significant for several reasons. First, it is the largest yet known from the Cedar Mountain Formation, yielding several dozen tracks from at least three stratigraphic levels. Second, it yields a variety of variably preserved theropodan track morphotypes that were previously unknown from the formation. Third, some of these theropodan tracks appear to be functionally didactyl, thus indicating probable dromeosaurid affinity. Based on the known skeletal faunas (Kirkland et al., 1993, 1997), it is possible that these didactyl tracks were produced by *Utahraptor* or some related dromeosaurid (Lockley and Peterson, 2002; White and Lockley, 2002).

The context of the tracks is also interesting since they occur as two distinctive assemblages, or ichnocoenoses, with different compositions and styles of preservation. The older track-bearing layer, which reveals only relatively shallow and well-preserved theropod tracks, is associated with well-bedded "gritty" sandstones with ripple marks and enigmatic invertebrate trails. By contrast the younger bed can be characterized as a homogenized "trampled" layer with sauropod, theropod, and probable ornithopod tracks that are, in most cases, very deep, sometimes resulting in impressive "three-dimensional" preservation of foot morphologies. The purpose of this paper is to describe the site in detail with special reference to the tracks and their morphology.

GEOLOGICAL SETTING

The track bearing levels are found on southward dipping bedding planes that crop out just north of the Delicate Arch

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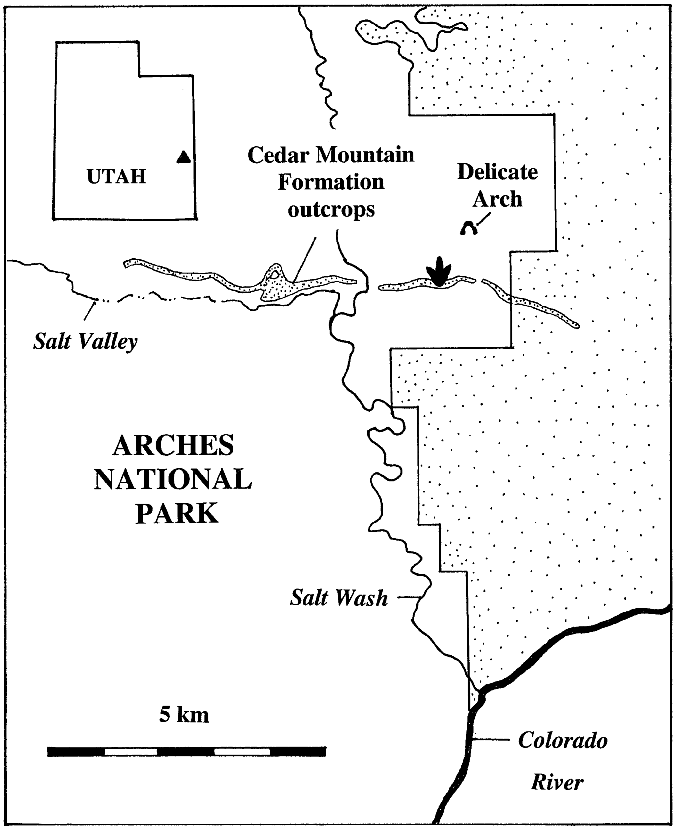

FIG. 1. Locality map of tracksite (track symbol) in east-west trending outcrops of the Cedar Mountain Formation, near eastern boundary of Arches National Park Monument (white area). Stippled area to east is Bureau of Land Management land.

viewpoint parking lot near the eastern boundary of Arches National Park. The stratigraphic section (Figs. 2 and 3) is well exposed and reveals a succession from the underlying Morrison Formation, through the Cedar Mountain Formation into the overlying Dakota Formation (Doelling et al., 1985).

The stratigraphy of the Cedar Mountain Formation is complex in the Arches region consisting, in ascending order, of the Barremian Yellow Cat Member, Poison Strip Sandstone, and the Aptian-Albian Ruby Ranch Member (Kirkland et al., 1993, 1997; Smith et al., 2001). The crest of the hogback consists of the Poison Strip Member, while the tracks occur abundantly at two stratigraphic levels in the basal part of the overlying Ruby Ranch Member (Figs. 3, 4, and 5) that crops out on the dip slopes to the south. There are also sparse traces of footprints at a third level.

MATERIALS AND METHODS

We made maps of track-bearing areas of both the lower and upper track-bearing surfaces, where significant concentrations of tracks occur. We also made latex molds and acetate film tracings of the most representative tracks. Latex molds, and plaster replicas of tracks were reposited in the CU Denver Dinosaur Tracks Museum. CU-MWC refers to specimens in the joint University of Colorado at Denver-Museum of Western Colorado collections. The "T" prefix (e.g., T 528-530) refers to tracings in the CU Denver Dinosaur Tracks Museum library.

DESCRIPTION OF TRACKS AND TRACKSITES

The lower track-bearing surface reveals a relatively simple track assemblage consisting mostly of theropod tracks (Fig. 4) and possibly some sauropod underprints. Tracings of these theropod tracks suggest one small narrow footed morphotype (CU-MWC 199.16: T 529) and a more common medium-size theropod (CU MWC 199.14–15 and 17–18: T 529–530 and 543–544). This surface also yields a number of enigmatic ?invertebrate trace fossils consisting of short (about 2 cm) sub-parallel indentations in curved or semicircular arrays that resemble miniature traces produced by the "caterpillar" track of a tank or bulldozer. The origin of these traces is unknown.

The upper track bearing surface (Fig. 5) is more complex consisting of a trampled bed that yields evidence of both saurischians (theropods and sauropods) and ornithischians (probable ornithopods and ankylosaurs, Fig. 6). Among the theropods are some well-preserved highly three-dimensional tracks (CU-MWC 199.19) and two apparently didactyl tracks (CU MWC 199.20–21) that may be attributable to dromaeosaurids (Fig. 7). The sauropod tracks (T. 530), probable ankylosaur track (T 545) and other miscellaneous tridactyl tracks (T 528) are shown in Figs. 5 and 6.

Saurischian Tracks

Saurischian tracks can be broadly divided into three categories: tridactyl theropod tracks, didactyl theropod tracks and sauropod tracks. The former category is the most varied, including tracks that vary in size (length) from about 20–35 cm (Figs. 4 and 5). Most of the best-preserved tridactyl tracks occur in trackway segments in the lower mapped level (Fig. 4). These indicate medium-sized animals (foot length about 27 cm) with narrow trackways and a step ranging from 85–110 cm. The two trackways (1 and 2) shown in Fig. 4, corresponding to replicas CU-MWC 199.14 and 199.15, produce speed estimates of 12 and 22 km/hr, respectively.

Two tracks from the upper track-bearing level are noteworthy. The first, a large robust track (Fig. 5C), appears different from those in the lower level. The second (Fig. 5D) shows exquisite three-dimensional preservation and appears to represent a different, gracile morphotype. Tracks of this size would match the foot of the type specimen of the coelurosaurian theropod *Nedcolbertia* (Kirkland et al., 1998), which is a juvenile, while the larger tridactyl tracks may represent adults.

Two medium-sized, isolated didactyl tracks from the upper track-bearing layer (Figs. 7A, B) appear to be attributable to dromeosaurs, as suggested by White and Lockley (2002) and Lockley and Peterson (2002). These specimens (CU-MWC

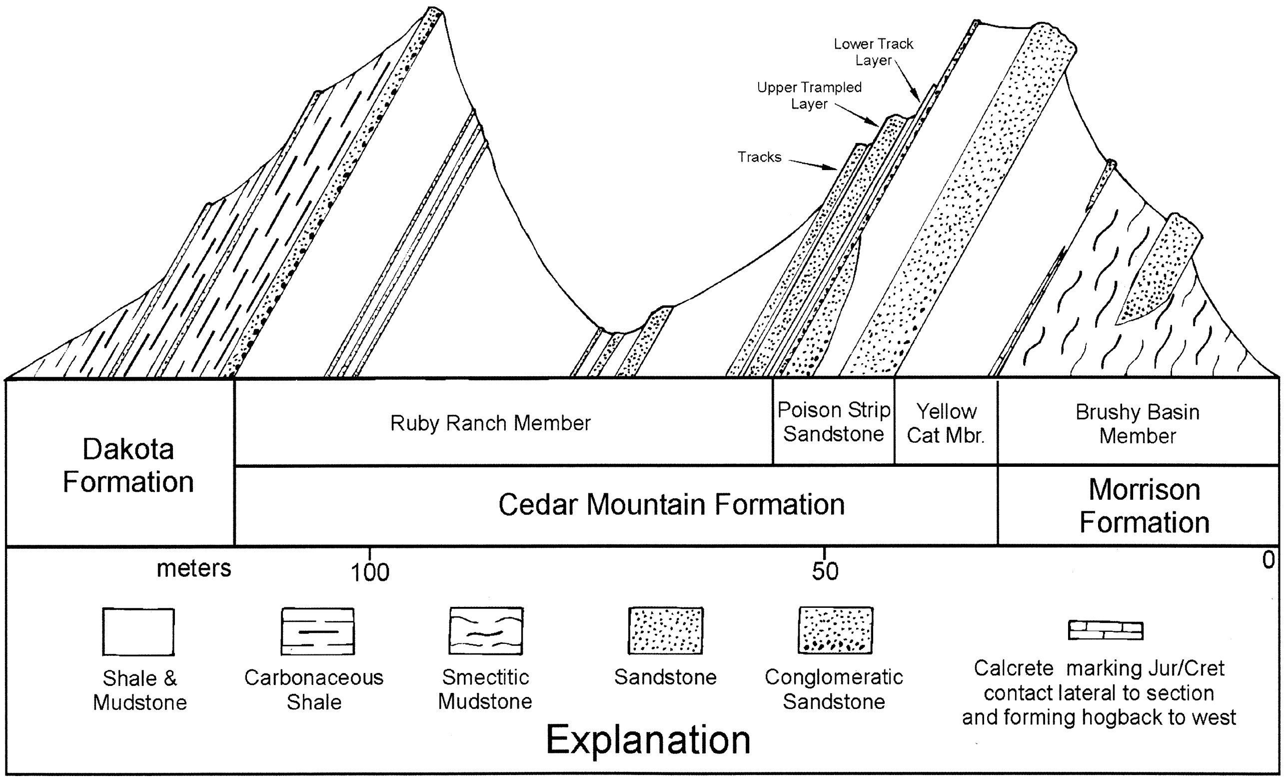

FIG. 2. Schematic, cross section of stratigraphy through the Cedar Mountain Formation in the eastern outcrops of Arches National park, near Delicate Arch viewpoint, showing track-bearing units in the basal part of the Ruby Ranch Member. Compare with Fig. 3.

199.20 and 199.21, respectively) measure 28 and 38 cm in length and represent left and right footprints, respectively. Unfortunately, owing to the relatively small exposures of bedding plane surface, these tracks are not preserved in the context of trackways that show consecutive steps. However, the tracks are deep and the absence of a "normal" digit II impression appears to be a primary morphological feature, rather than the result of poor preservation. We have compared the tracks with the reconstructed foot of *Utahraptor*, made by Rob Gaston, who discovered the type material (Kirkland et al., 1993). The track and skeletal morphologies correspond, and the larger track (CU-MWC 199.21) is a close match for size. However, it is outside the scope of this paper to undertake a detailed analysis of dromeosaur foot morphology in relation to the small sample of didactyl tracks currently known from the Cretaceous. In any event, such a study would benefit from the discovery of additional material. For example, John Bird (personal communication) reports two sites with possible didactyl tracks. The first, from the Cleveland Lloyd Quarry area, Emery County, Utah, was mentioned and briefly illustrated by Lockley and Hunt (1994, fig. 5). Another site has yet to be investigated.

Didactyl tracks of this type from the Cretaceous of China (Zhen et al., 1995) have been named *Velociraptorichnus* (Fig. 7C). However, these tracks are small by comparison with the Arches didactyl tracks, and we suggest caution in applying this name, as the Chinese nomenclature is also based on relatively limited material.

Sauropod trackway segments have been identified in the mapped portion of the upper track bearing bed. These consist primarily of pes tracks with recognizable toe impressions. The trackway segments (Fig. 6A) indicate an animal with a pes measuring about 58 by 48 cm (length and width) a stride of 144 cm and an internal trackway width of about 30 cm. Thus the trackways appear to be wide gauge, as is the case with the classic sauropod trackways named *Brontopodus* from the Albian of Texas (Farlow et al., 1989). This name may be provisionally applied here. Another well-defined pes track measures 80 by 45 cm (Fig. 6B).

Ornithischian Tracks

There are also two track types that appear to be of ornithischian affinity. The first represents probable ornithopod tracks. For example a track that measures about 47 cm wide by 42 long (Fig. 6B) was recorded in the mapped area of the upper trampled level, and another similar track was found at the same stratigraphic level about a mile to the west. The second type, a probable ankylosaur track is represented by a single large manus impression (Fig. 6C) that measures about 57 cm wide by 43 long from the upper trampled layer about a mile east of the main site.

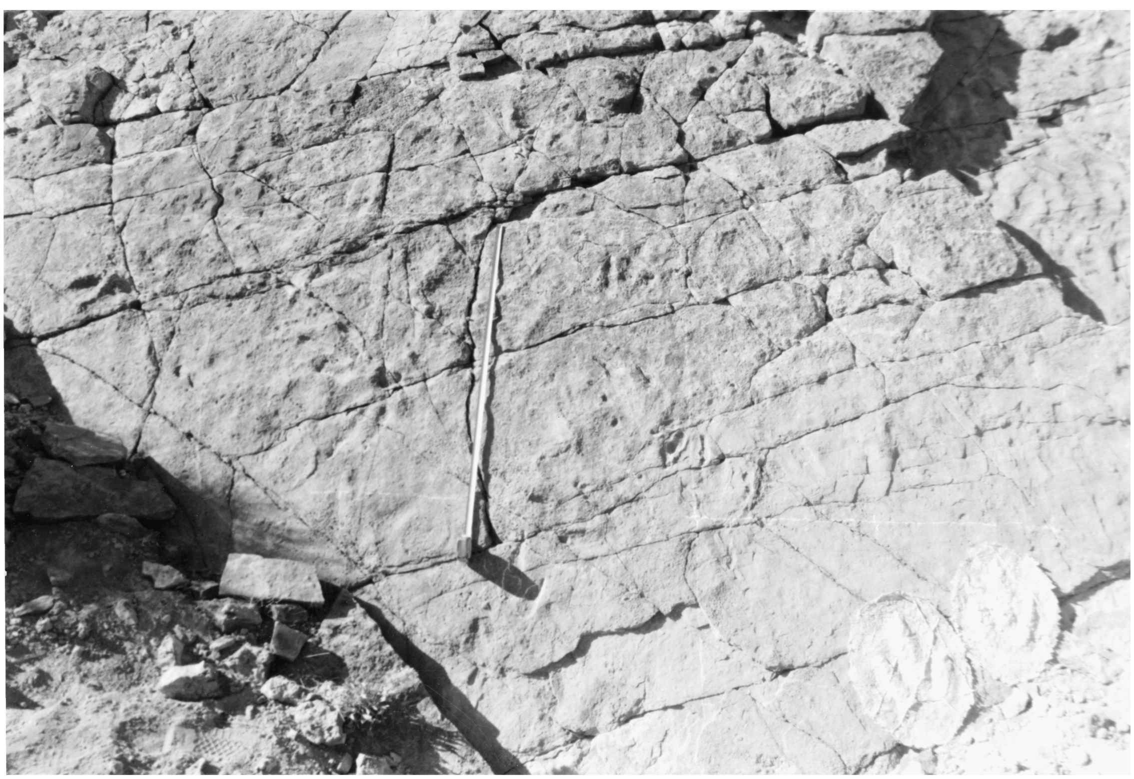

FIG. 3. Photographs of site: **Top**: general view of dip-slope outcrops looking westwards. **Bottom**: theropod tracks from lower track-bearing level. Tape scale 1 m. Note two latex molds (CU-MWC 199.14 and 199.15) lower right.

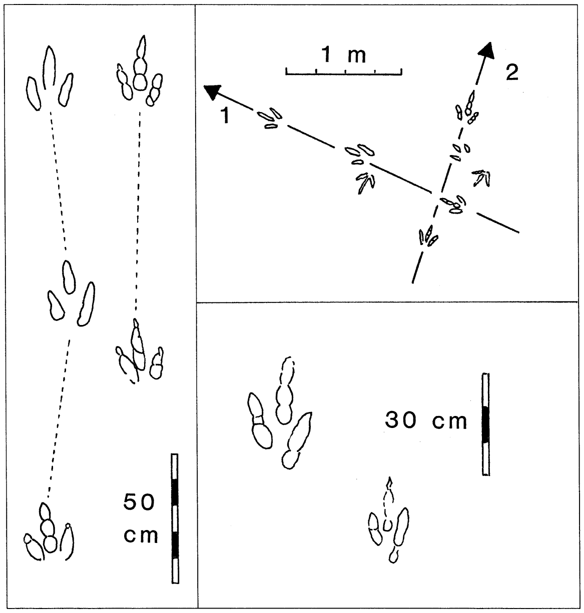

FIG. 4. Theropod tracks and trackways from the lower track bearing level. **Left**: two trackway segments (1 and 2) from main track area (map, top right). **Lower right**: two isolated tracks from the same surface.

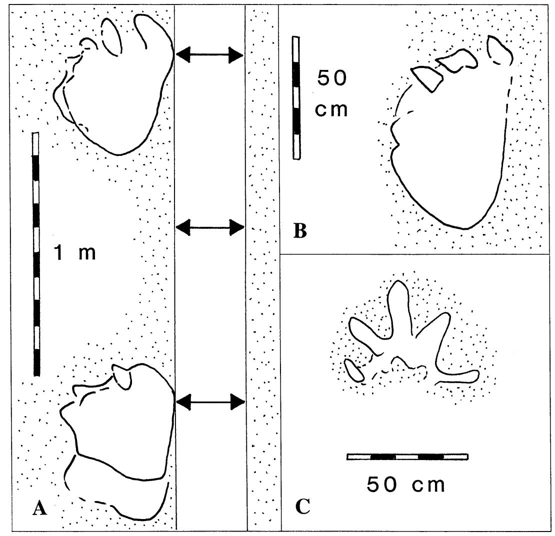

FIG. 6. **A**: Partial sauropod trackway showing two left pes impressions and inner pes to pes trackway width (black arrows). **B**: isolated large sauropod pes impression. **C**: probable ankylosaur manus track. All tracks from upper track-bearing levels.

OVERVIEW AND IMPLICATONS OF THE ICHNOLOGICAL ASSEMBLAGES

The dinosaur tracksite at Arches National Park is significantly more diverse than those previously described. The most recent review (Lockley et al., 1999) essentially only lists isolated track occurrences from five tracksites that are widely scattered in space and time within three of the four members of the Cedar Mountain Formation. For example, a few theropod, ornithopod, and poorly preserved sauropod tracks are known from three sites in the Barremian (125–119 ma) Yellow Cat Member. No tracks have been reported from the Poison Strip Sandstone. Prior to the present study only a single, probable ornithopod track had been reported from the Aptian-Albian Ruby Ranch Member, and the largest sample consisted of a handful of tracks, from the Albian-Cenomanian Mussentuchit Member at Long Walk Quarry (DeCourten, 1991, 1998). The total sample consisted of

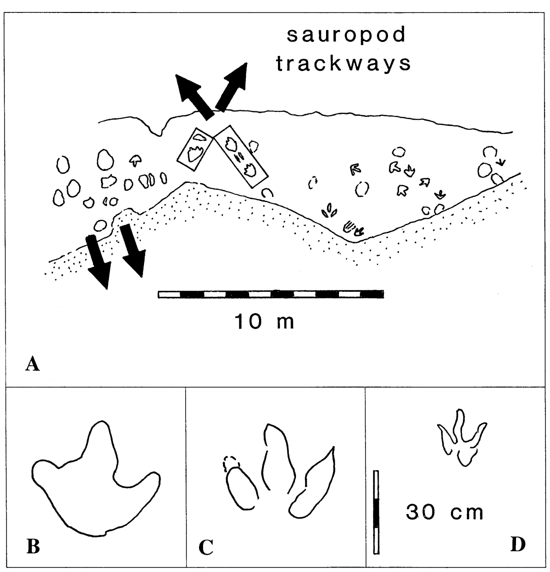

FIG. 5. **Top**: map (A) of a part of the upper track bearing level showing at least four probable sauropod trackways (compare with Fig 6). **Below**: three isolated tridactyl tracks, including possible ornithopod track (B) and two theropod tracks (C and D).

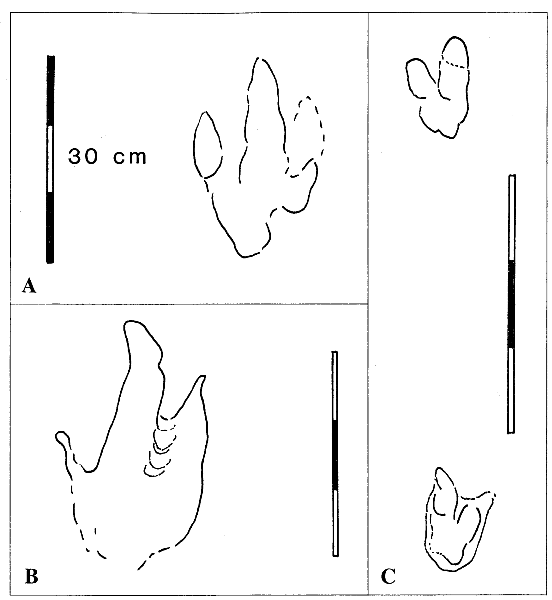

FIG. 7. **A** and **B** respectively: probable dromeosaurid tracks (199.20 and 199.21) from the upper track-bearing level. **C**: two consecutive *Velociraptorichnus* tracks from the Cretaceous of China (right). All scale bars 30 cm.

little more than a dozen isolated tracks from five geographical sites, ten of which were illustrated in the aforementioned "preliminary report" (Lockley et al., 1999). One additional (sixth) tracksite, yielding two isolated ornithopod track casts, was discovered in the Mussentuchit Member just north of the type area for that member. These specimens were collected by the College of Eastern Utah, in Price, but have not been described: see Kirkland et al. (1997) for stratigraphic context. By contrast the Arches site (the seventh) discussed herein, has yielded at least 50 tracks in two distinctive bedding plane assemblages. It is the first Cedar Mountain tracksite to yield footprints in trackway sequences (Figs. 4 and 6).

The Arches site essentially yields all the main dinosaur track types so far found at all other previously discovered sites. A minimum estimate of faunal diversity suggests the presence of several tridactyl theropods (probably three morphotypes), a didactyl theropod (probably a dromeosaur) a wide gauge sauropod, an ornithopod and an ankylosaur. This suggests a provisional estimate of seven dinosaurian taxa.

It is instructive to divide the ichnological list from this locality into two distinct ichnocoenoses. The first is theropod-dominated with faint traces of sauropod tracks as underprints, associated with a ripple marked sand substrate. This can be referred to provisionally as a "saurischian" ichnocoenosis. This ichnocoenosis fauna associated with an inferred lake shoreline paleoenvironment. The second ichnocoenosis, at a higher stratigraphic level, includes tracks representative of both the major dinosaurian orders and so can be provisionally labeled a "saurischian and ornithischian" ichnocoenosis. This track-bearing level is a heavily trampled silty substrate representing a different paleoenvironment probably a pond/swamp.

It is uncertain whether the difference between the lower diversity ichnocoenosis, with no more than three distinct track types, and the upper ichnocoenose with at least seven track types is of paleobiological and paleoenvironmental significance. The difference in sedimentary facies is interesting. Based on density and depth of tracks at the two stratigraphic levels, it is clear from the great depth of all footprints at this level that the upper level represents a much wetter substrate.

COMPARISONS BETWEEN SKELETAL REMAINS AND ICHNOFAUNAS

In recent years the Cedar Mountain dinosaur faunas have become quite well known. (Carpenter and Kirkland, 1998; Kirkland, 1998a, b; Kirkland et al., 1997, 1998). Among saurischians are the following genera: the small coelurosaur *Nedcolbertia* (Kirkland et al., 1998), the large theropod *Acrocanthosaurus*, the dromaeosaurs *Utahraptor* (Kirkland et al., 1993) and *Deinonychus* and the brachiosaurid sauropods *Pleurocoelus* and *Cedarosaurus* (Tidwell et al., 1999), the titanosauromorph sauropod *Venenosaurus* (Tidwell et al., 2001) and true titanosaurid sauropods (Britt and Stadtman, 1997). Among ornithischians the ornithopods *Iguanodon* (Galton and Jensen, 1978), *Eolambia* (Kirkland, 1998b), *Planicoxa* (DiCroce and Carpenter, 2001) *Tennontosaurus* sp, and *Zephyrosaurus* sp. have been recorded, along with the ankylosaurs *Gastonia* (Kirkland, 1998a), *Sauropelta*, *Cedaropelta* and *Anamantarax* (Carpenter et al., 1999, 2001).

TABLE 1
Dinosaurian faunas from the middle members of the Cedar Mountain Formation.

Poison Strip Sandstone and lower Ruby Ranch Member Aptian 119–112 mya	**Upper Ruby Ranch Member Albian 112–100 mya**
Theropoda	Theropoda
Allosauridae	?Allosauridae
New genus.*	*Acrocanthosaurus* sp.*
Dromaeosauridae	Sauropoda
Deinonychus sp.*	Brachiosauridae
Indeterminate Family	cf. *Pleurocoelus*
cf. Richardoestesia sp.	(= *Astrodon*) sp.*
Sauropoda	Ankylosauria
Brachiosauridae	Nodosauridae
Pleurocoelus	cf. *Sauropelta* sp. (large)*
(= *Astrodon*) sp.*	Ankylosauridae
Titanosauromorpha	*Cedaropelta bilbyhallorum*
*Venenosaurus dicrocei**	Ornithopoda
Ankylosauria	Iguanodontia
Polacanthidae	cf. *Tennontosaurus* sp.*
Gastonia sp.	
Nodosauridae	
Cf. *Sauropelta* sp.*	
Ornithopoda	
Iguanodontia	
*Planicoxa penenica**	

*Indicates possible trackmakers for tracks from Arches site. See text for details.

It is important to note that not all these genera have been found in the Ruby Ranch Member. For the purposes of this tentative comparison between skeletal remains and track types, we include faunal compilations for the Ruby Ranch Member (Table 1) divided into two lists: 1) the Aptian–? Early Albian (119–105 mya) Poison Strip Sandstone and lower Ruby Ranch Member and 2) the Albian (102–100 mya) upper Ruby Ranch Member (Smith et al. 2001; Ludvigson et al., 2002).

In addition, to genera already identified positively or with a high level of confidence, there are a number of taxa that have not yet been identified at the generic or species level. It is anticipated, therefore, that the existing faunal lists will be modified in future.

The Ruby Ranch Member of eastern Utah preserves an extensive dinosaur fauna that is as yet only partially studied. Saurischians include theropods represented by dromaeosaurid teeth identified as *Deinonychus*, a large carnosaurid with coarsely serrated teeth (Aptian), and the giant high spined carnosaur *Acrocanthosaurus* (Albian), and brachiosaurid sauropods assigned to *Pleurocoelus* (= *Astrodon*) (Albian) and the Titanosauromorpha *Venenosaurus* (Aptian). Ornithischians include the Ankylosaurs *Gastonia* sp. (Polacanthidae) (Barremian-Aptian, Carpenter, 2002), *Cedaropelta* (shamosaurine) (Albian), *Sauropelta* sp. (Nodosauridae) (Aptian-Albian) and the ornithopods (iguanodontids) *Planicoxa* (Aptian) and Tennontosaurus sp. (Albian).

Most of the tracks described from the Arches site could be ascribed to representatives of the skeletal fauna listed in Table 1. For example, the large theropod track found at the upper track level (Fig. 5) could be assigned to *Acrocanthosaurus*, as suggested by Farlow (2001) for similar Albian age tracks from Texas. Similarly, the didactyl tracks could be assigned to a dromeosaurid such as *Deinonychus*, known from the Ruby Ranch Member, or the larger *Utahraptor*, known from the older Yellow Cat Member. Because the sauropod tracks are wide-gauge (i.e., resembling ichnogenus *Brontopodus*) they can tentatively be attributed to brachiosaurids (such as *Pleurocoelus*) or titanosauromorphs, both of which were probably wide-gauge (Lockley et al., 1994; Lockley and Hunt, 1995; Henderson, 2002). The ornithopod tracks are also consistent with those attributed to iguanodontids (e.g., *Tennontosaurus* or *Planicoxa* from the Ruby Ranch Member), or *Iguanodon* (from the older Yellow Cat Member), and the large ankylosaur manus might be attributed to a genus such as *Sauropelta*. Other ankylosaurs might also have been responsible for making the large track (Fig. 6) though some, e.g., *Gastonia* were probably too small to make this track.

DISCUSSION AND CONCLUSIONS

As shown earlier, Cedar Mountain faunas and ichnofaunas are well dated. Thus, it is possible to compare the track types and probable trackmakers with footprints and faunas from time-equivalent deposits. Among the best-known North American ichnofaunas that are equivalent in age to Ruby Ranch Member of the middle part of the Cedar Mountain Formation (Aptian-Albian) are those reported from the Aptian-Albian of western Canada (Currie and Sarjeant, 1979; McCrea et al., 2001), South Dakota (Barremian) (Lockley et al., 2001), Colorado (Albian) (Lockley et al., 1992; Lockley and Hunt, 1995; Kurtz et al., 2001), and Texas (Albian) (Farlow et al., 1989). Ichnofaunas of this age have also been reported recently from the Aptian of Maryland in the eastern United States (Stanford and Lockley, 2002) and can be compared with skeletal faunas (Krantz 1998; Lipka, 1998).

Despite the fact that most of these ichnofaunas are known from dozens of sites, many are relatively low in diversity. For example, the Albian aged Texas ichnofaunas from carbonate platform facies are dominated by sauropod (ichnogenus *Brontopodus*) and large theropod tracks that have been attributed to *Acrocanthosaurus* (Farlow, 2001). However, authenticated reports of ornithischian tracks are essentially unknown from carbonate facies in Texas. This low diversity (only two common ichnotaxa) from more than 50 localities seems impoverished in comparison with the Cedar Mountain. Similarly the Dakota Group megatracksite or "dinosaur freeway" (Lockley et al., 1992) also has a dinosaur track ichnodiversity of only two consisting of a *Caririchnium* (ornithopod) and *Magnoavipes* (theropod) assemblage, with a few crocodilian and bird tracks. Most of these sites are in the uppermost part of the Dakota Group dated as latest Albian or early Cenomanian. This ichnofauna is also found in Cenomanian siliciclastic facies of Texas (Lee, 1997) and so is probably younger than any of the Ruby Ranch assemblages and more closely correlative with the Mussentuchit Member. Only in the middle Albian, part of the Dakota Group, do we find different ichnofaunas dominated by ankylosaur tracks (Kurtz et al., 2001). Ankylosaur dominated ichnofaunas are also typical of some of the western Canada sequences (McCrea, et al., 2001). These western Canada ichnofaunas are dominated by theropod, bird, and ornithopod tracks, with a conspicuous absence of sauropod tracks in most assemblages. Similar ichnofaunas are found in the Barremian-Aptian Lakota Group of South Dakota (Lockley et al., 2001). In recent years many bird tracks have been reported from the Cretaceous (Lockley et al., 1992b; Lockley and Rainforth, 2002).

The distribution of large herbivorous dinosaurs, and other groups, is to some extent controlled by facies and habitat preference, and migration or intercontinental faunal exchange. For example, ankylosaurid dinosaurs seem to reach a zenith in the Albian, and appear to be particularly abundant in association with humid high latitude facies in Canada. To date the Cedar Mountain has the highest diversity of ankylosaurs in the world (Carpenter et al., 1999), which is also reflected in the ichnofaunas (McCrea, 2001). Similarly, sauropod tracks are rare at higher latitudes, above 30° and humid, coal-bearing coastal plain facies where ornithischian (ornithopod) tracks are common (Lockley, 1991; Lockley et al., 1994). Sauropods also appear to be absent in western North America from latest Albian until the latest Campanian, giving rise to the concept of a sauropod hiatus (Lucas and Hunt, 1989).

The Cedar Mountain and particularly the Ruby Ranch Member ichnofauna is evidently quite representative of the formations' skeletal faunas. Dinosaur faunas with compositions similar to those found in the Cedar Mountain Formation are widely distributed across North America in Montana, Wyoming, Texas, Oklahoma, and even Maryland. Based on North American correlations the Ruby Ranch dinosaurs indicate an Albian age of approximately 110 million years. Several of the nodosaurid, brachiosaurid, and primitive iguanodontid dinosaurs are not known from other continents at this time. It has been proposed that, as shallow seas flooded Europe, North America was an isolated island continent (Carpenter et al., 2002). The uppermost Ruby Ranch Member on the north end of the San Rafael Swell has recently yielded the remains of several shamosaurine ankylosaurs as such as *Cedaropelta cedarpelta* (Carpenter et al., 2001). This dinosaur indicates the first tentative connections were being made with Asia at this time. Although nodosaurids continued to be important in North America until the end of the Cretaceous, the primitive iguanodontians and brachiosaurids apparently went extinct at the end of Cedar Mountain deposition. (see Lucas and Hunt, 1989, for discussion of sauropods).

The Cedar Mountain ichnofaunas, although known from only a few localities, provide evidence of diverse dinosaur-dominated faunas. Although non-dinosaurian tracks are currently unknown, ichnofaunas such as those reported herein from the Ruby Ranch Member at Arches National Monument appear to sample the entire saurischian and ornithischian dinosaur diversity at least in a general sense. For example, the diversity of unequivocally identified dinosaur types in the lower and upper Ruby Ranch successions (Table 1) is 9 and 5, respectively. The estimated diversity based on dinosaur track types is about 7.

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